Perspectives on Worldwide Light-Duty Emissions and Regulations

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SAE 2014 Light Duty Emissions Symposium
Troy MI
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icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

the ICCT: mission and activities

The mission of ICCT is to dramatically improve the environmental performance and efficiency of cars, trucks, buses and transportation systems in order to protect and improve public health, the environment, and quality of life.

- Non-profit research organization
- Air pollution and climate impacts
- Focus on regulatory policies and fiscal incentives
- Activity across modes including aviation and marine
- Global outreach, with special focus on largest markets

Index

- Global Emissions and Vehicle Standards
- Technical Approaches for Compliance
- In-Use Diesel NOx Emissions

Global Emissions and Vehicle Standards

Beijing Crazy-Bad Pollution

Tiananmen Square at dangerous levels of air pollution on January 23, 2013 in Beijing, China
Source: Forbes (Image credit: Getty Images via @daylife)
http://www.forbes.com/sites/jackperkowski/2013/07/29/china-getting-serious-about-air-pollution/

100 Highest Polluted Cities Worldwide (PM10)

World Health Organization, **Urban outdoor air pollution database,** September 2011

Rank	Country	City	Annual mean PM10 ug/m3
1			372
2			279
3			254
4			251
5			251
6			229
7			219
8			216
9			215
10			209
11			200
12			198
13			193
14			189
15			186
16			185
17			183
18	Iran	Qom	176
19	India	Indore	174
20	Iran	khoramabad	168
21	India	Agra	165
22	United Arab Emirates	Al Ain	158
23	Saudi Arabia	Riyadh	157
24	Saudi Arabia	Al-Hafouf	151
25	China	Lanzhou	150
26	India	Kolkata	148
27	Turkey	Van	146
28	Senegal	Dakar	145
29	Saudi Arabia	Makkah	142
30	China	Xining	141
31	China	Urumqi	140
32	India	Faridabad	139
33	Egypt	Greater Cairo	138
34	Mexico	Mexicali	137
35	India	Jabalpur	136
36	Bangladesh	Dhaka	134
37	India	Mumbai	132
38	India	Dhanbad	131
39	Iran	Ilam	129
40	Saudi Arabia	Jeddah	129
41	India	Allahabad	128
42	Iran	Bushehr	125
43	Iran	Kerman	125
44	China	Jinan	123
45	Kuwait	Kuwait City	123
46			122
47			121
48			121
49	India	Patna	120
50	Bosnia and Her	Sarajevo	117
51	United Arab En	Abu Dhabi	117
52	India	Meerut	115
53	China	Xi'an	113
54	India	Jaipur	112
55	Iran	Qazvin	112
56	Indonesia	Medan	111
57	China	Chengdu	111
58	China	Hefei	111
59	China	Shenyang	110
60	Saudi Arabia	Yanbu	108
61	Nepal	Kathmandu Val	106
62	China	Taiyuan	106
63	India	Varanasi	106
64	China	Chongqing	105
65	China	Wuhan	105
66	Iran	Esfahan	105
67	China	Shijiazhuang	104
68	Turkey	Konya	104
69	Turkey	Kars	103
70	Iran	Hamedan	103
71	Iran	Arak	102
72	China	Harbin	101
73	China	Tianjin	101
74	China	Nanjing	100
75	Turkey	Denizli	100
76	China	Zhengzhou	99
77	India	Pune	99
78	Turkey	Hatay	98
79	India	Nagpur	98
80	Ghana	Accra	98
81	China	Hangzhou	97
82	Iran	Tehran	96
83	Myanmar	Yangon	96
84	Turkey	Erzurum	95
85	India	Bhopal	93
86	China	Changsha	92
87	India	Vijayawada	91
88	Mexico	Tecate	90
89	China	Yinchuan	90
90	India	Bangalore	90
91	India	Rajkot	89
92	Myanmar	Mandalay	87
93	India	Hyderabad	87

Top Ten:

Iran: 4

India: 2

Pakistan: 2

Mongolia: 1

Botswana: 1

Beijing: 47

Mexico City: 181

Los Angeles: 472

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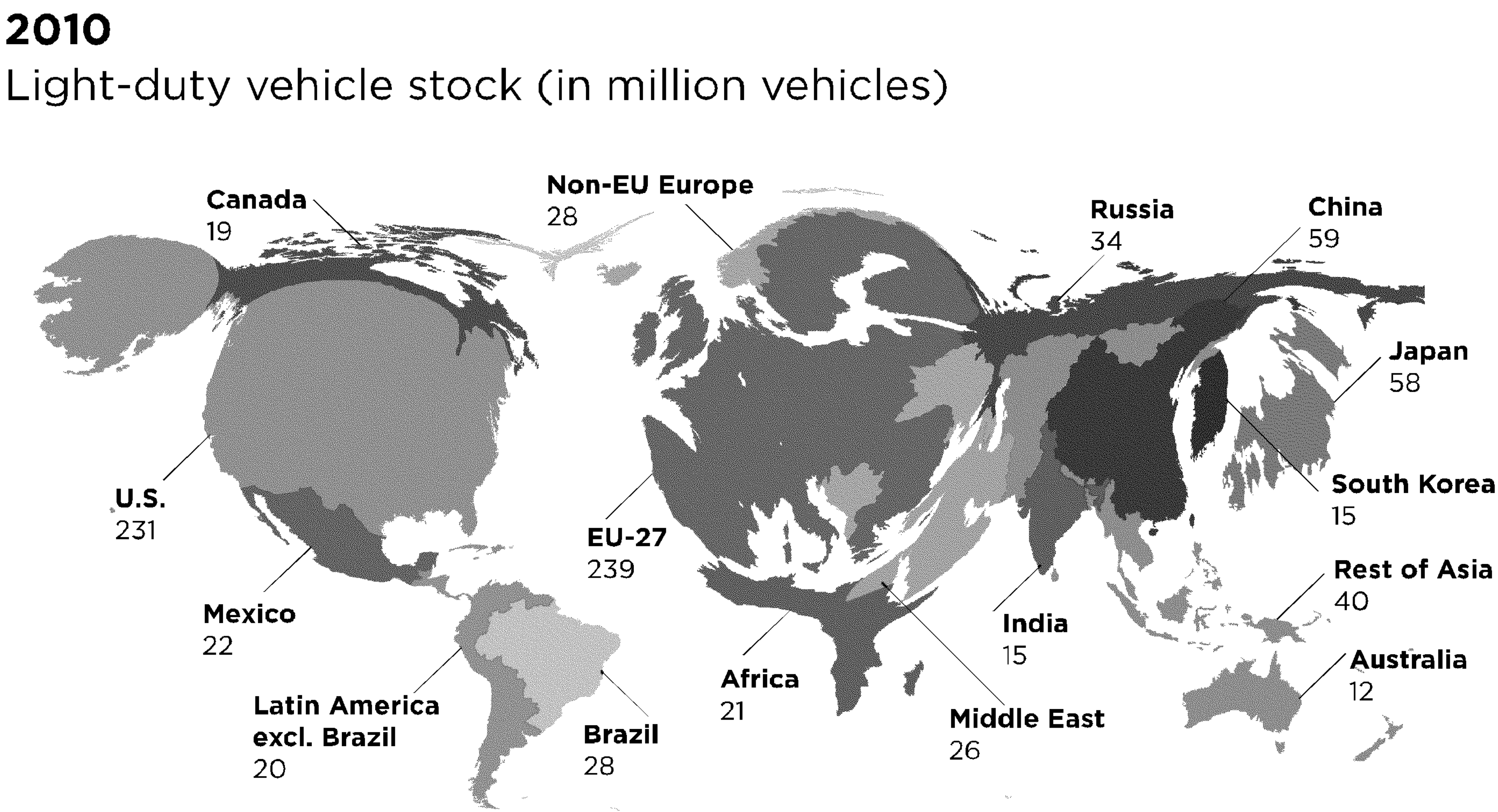
Global car fleet

Number of cars and vans on the road in 2010



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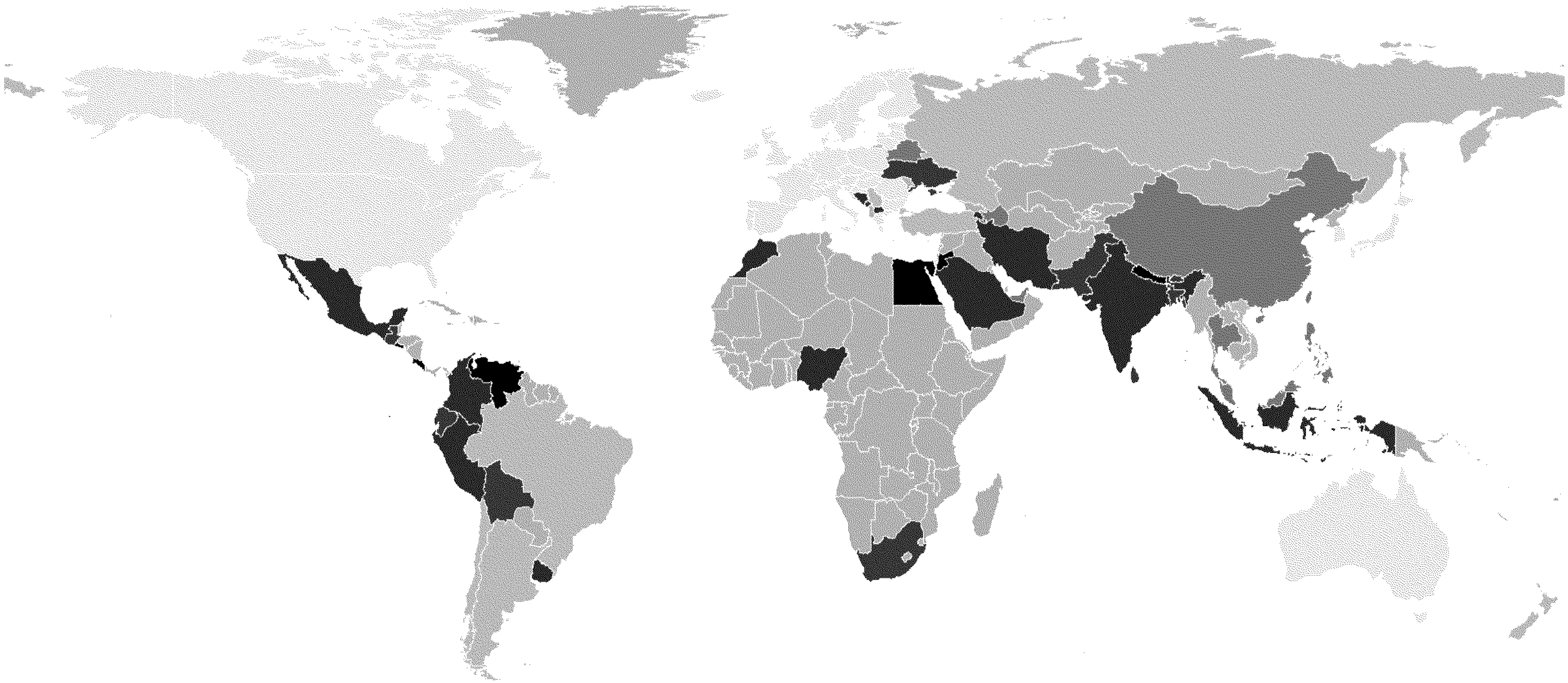
Vehicle emission standards worldwide



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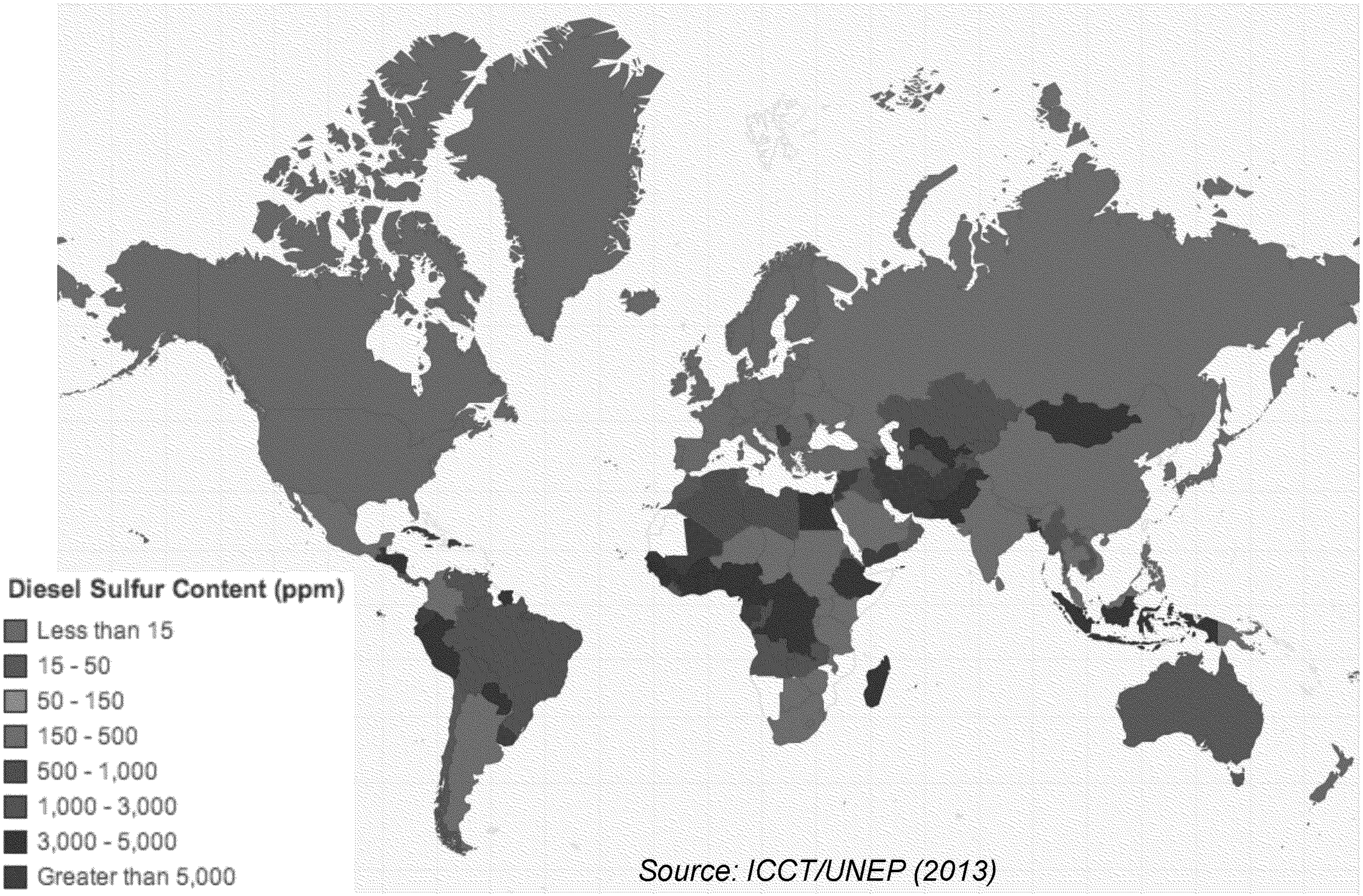
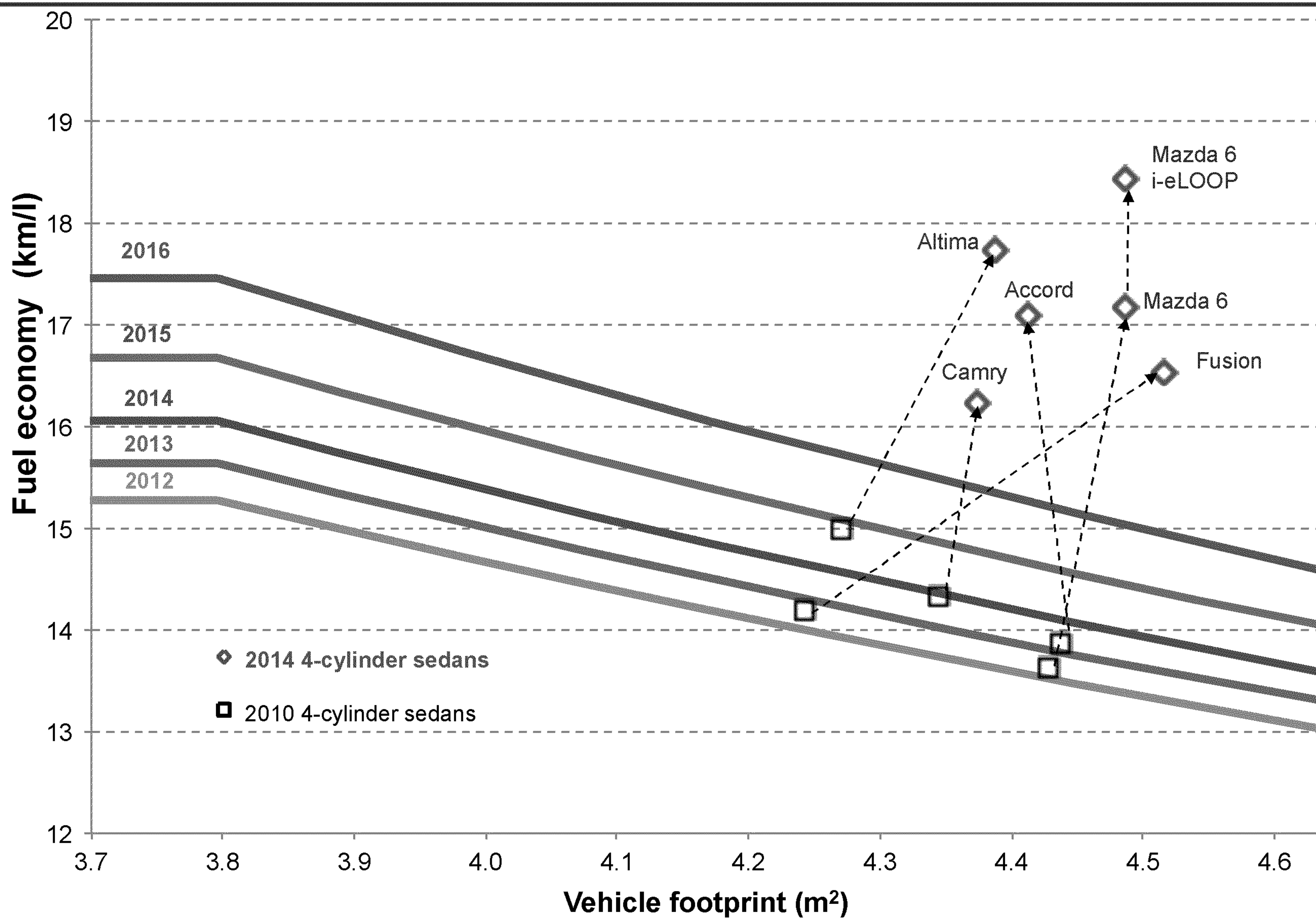
World map by diesel sulfur levels

Most emerging markets moving to 50 ppm; not 10 ppm



Standards drive technology upgrades…

(example: high-selling passenger cars in the US, 2010 to 2014)



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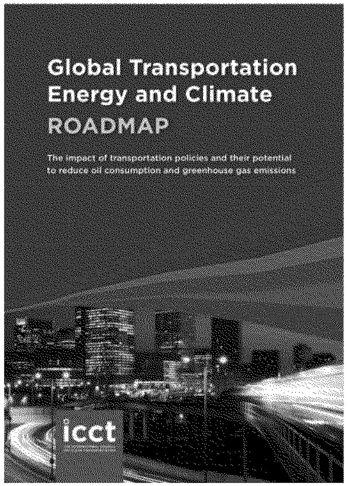
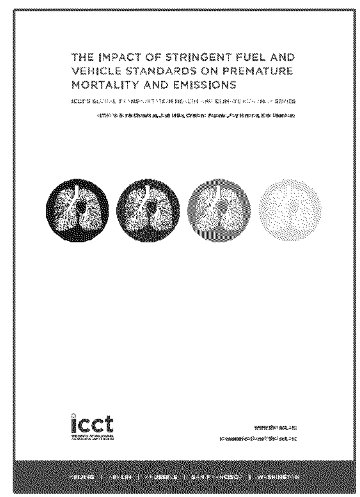
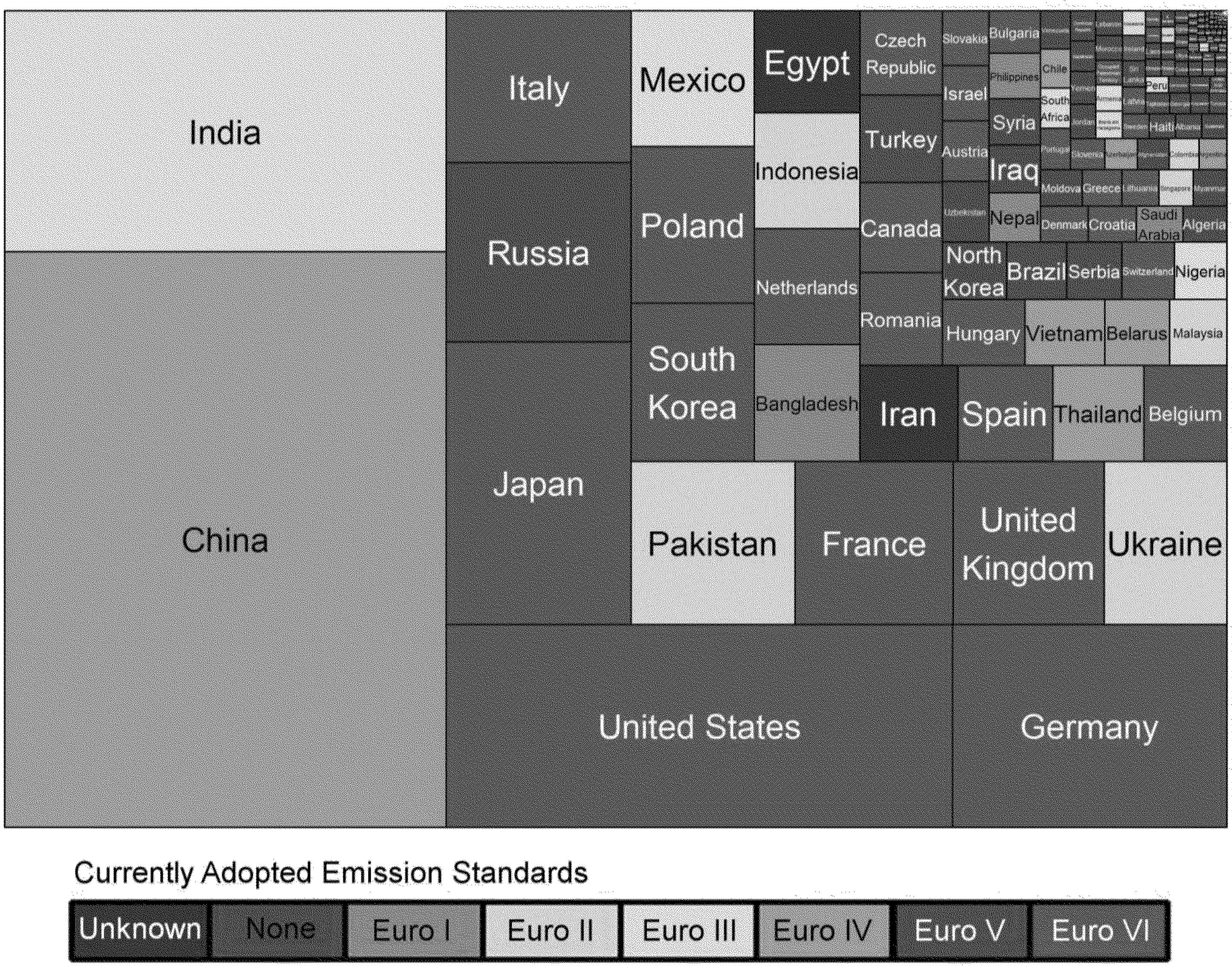
Global Transportation Roadmap Series



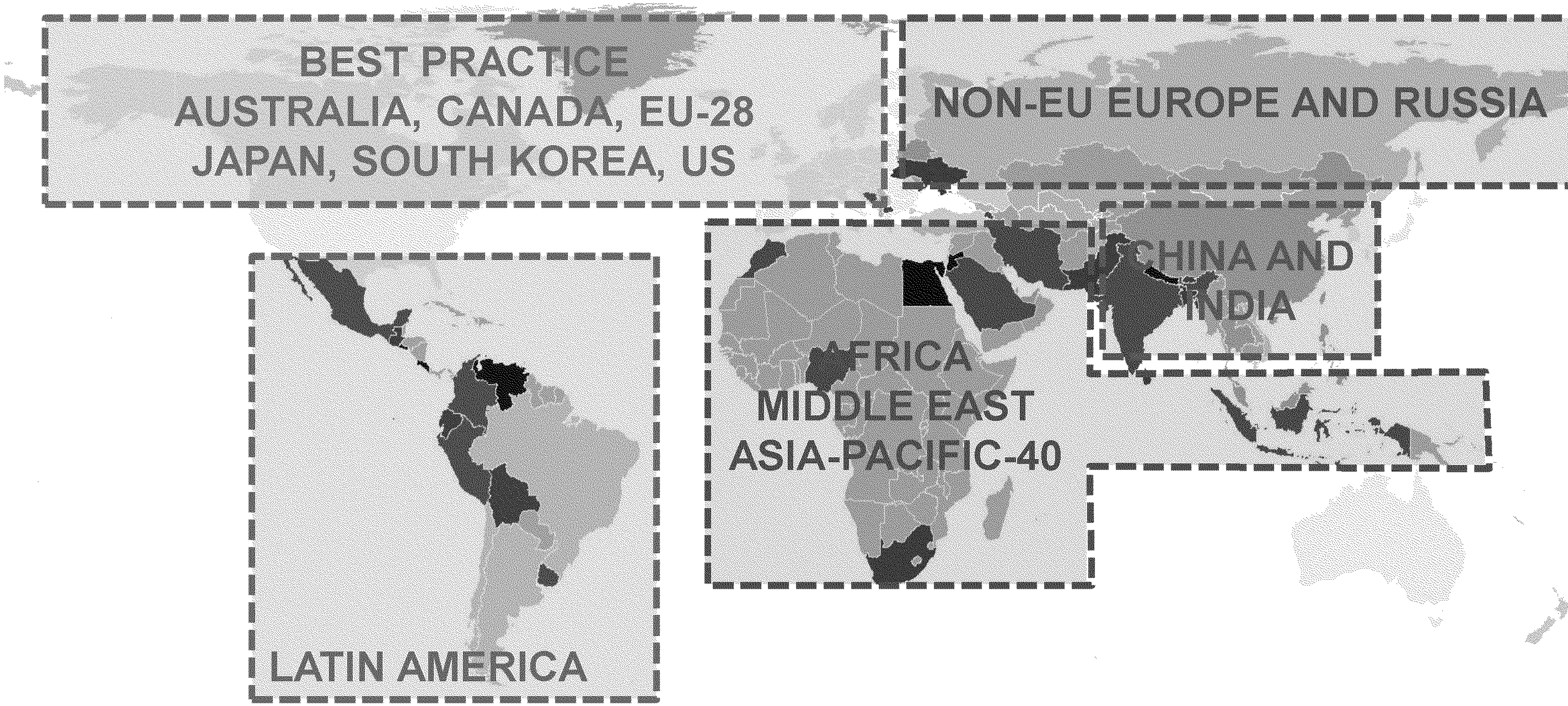


Early Deaths from Vehicle Emissions

(pictured: estimated distribution of early deaths from vehicle emissions by country and emission standard, 2013)

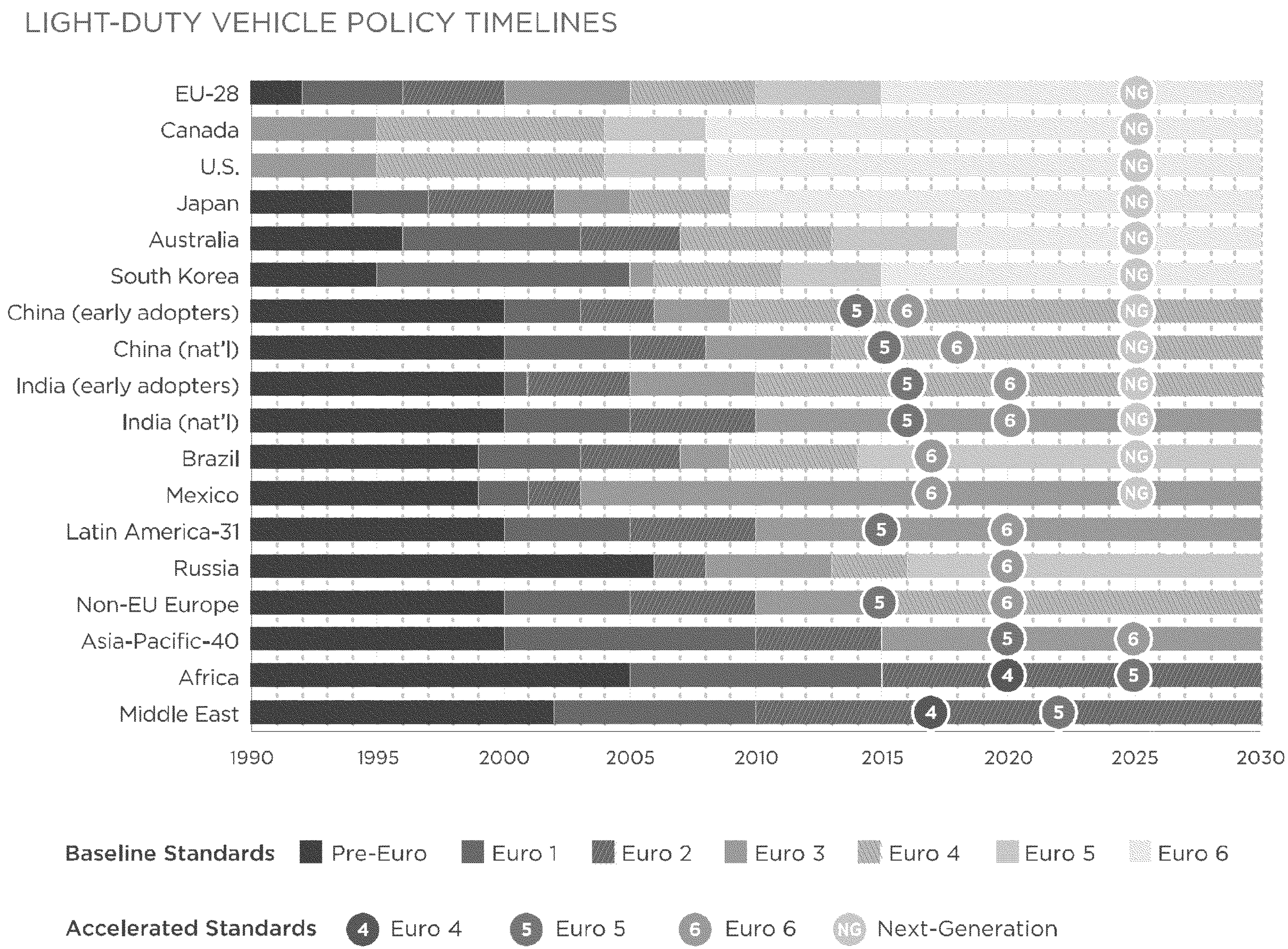


Vehicle emission standards worldwide

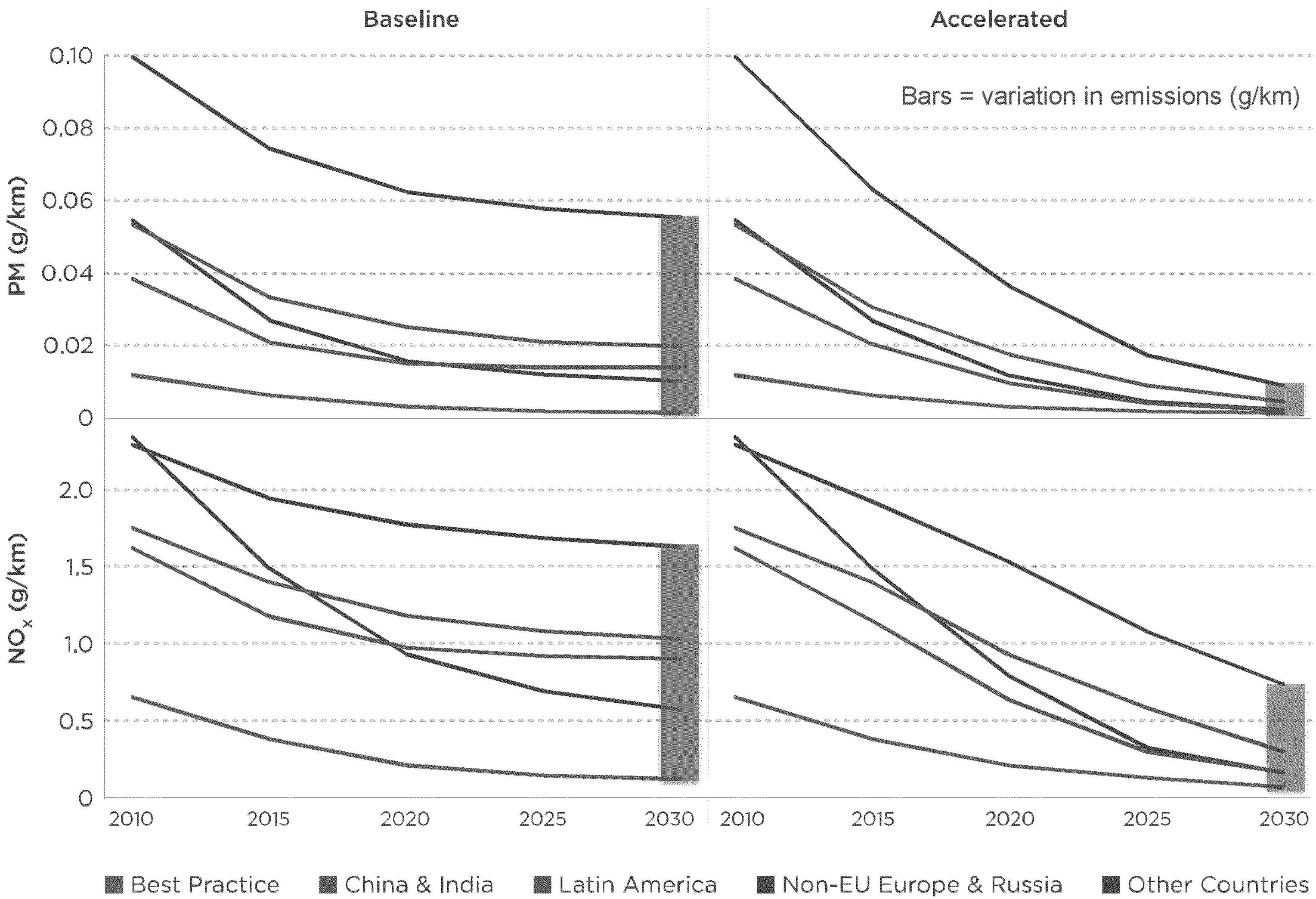


Policy roadmap towards cleaner vehicles and fuels

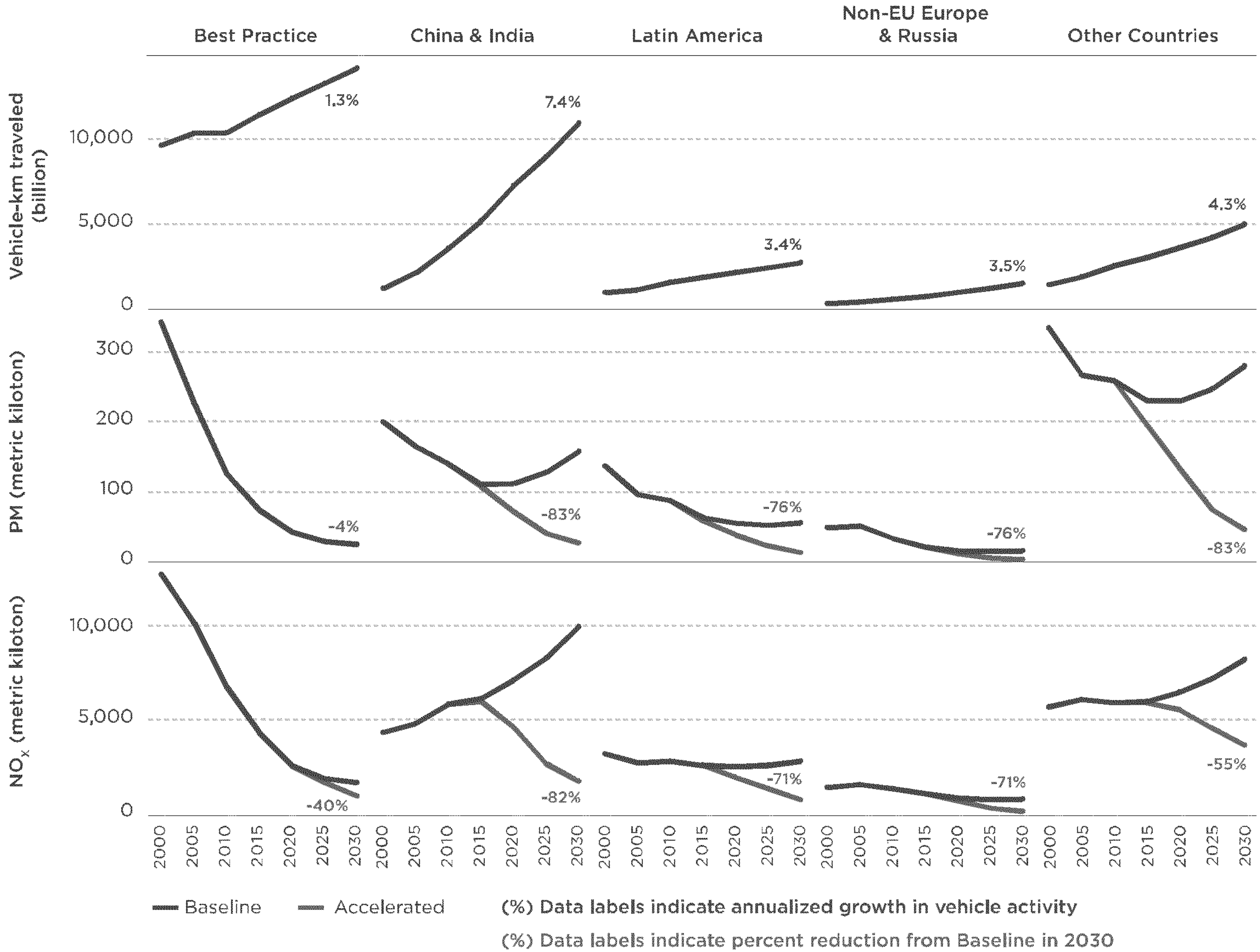
LDV Standards Timeline



…they drive convergence in average emission levels…



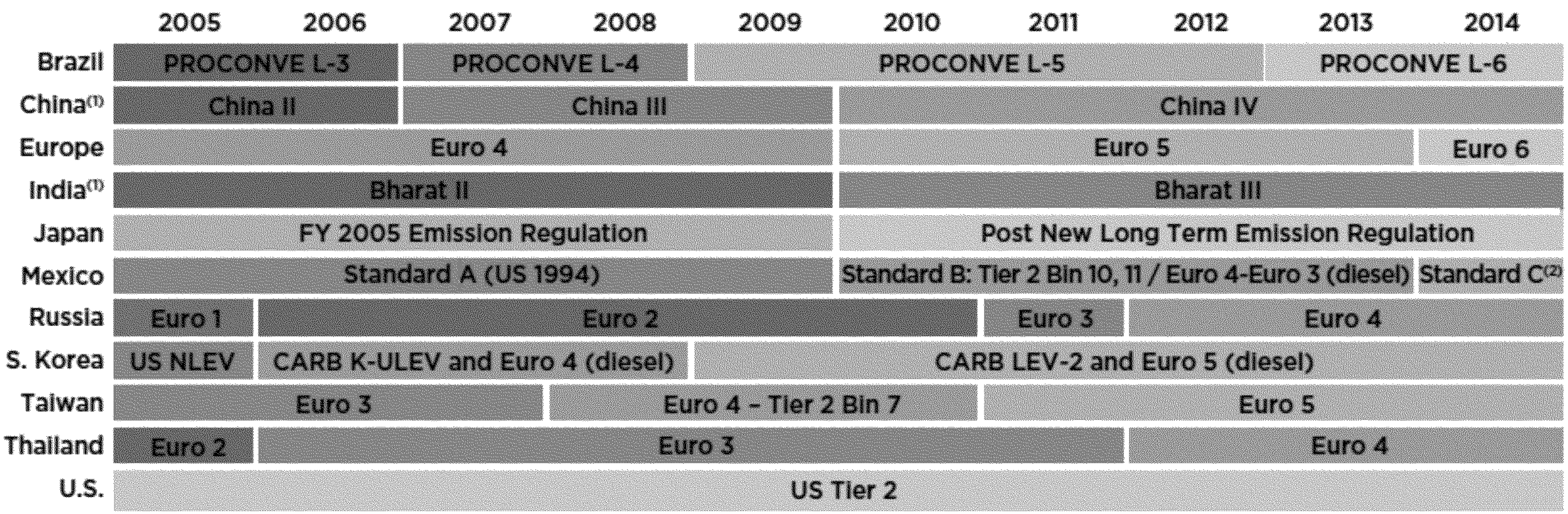
…they make a difference in air quality…



Technical Approaches for Compliance

Background
ICCT Study of Cost of Emission Control Technologies

- Standards are spreading around the globe
- Cost of adopting new technologies in LDVs is a prominent issue during regulatory negotiations worldwide
- Existing cost estimates were primarily from LEVII/Tier 2 rulemakings – over a decade out of date



(1) Major cities have introduced accelerated adoption schedules – timelines in this table reflect nationwide adoption
(2) Implementation schedule dependent on the availability of low sulfur fuel nationwide

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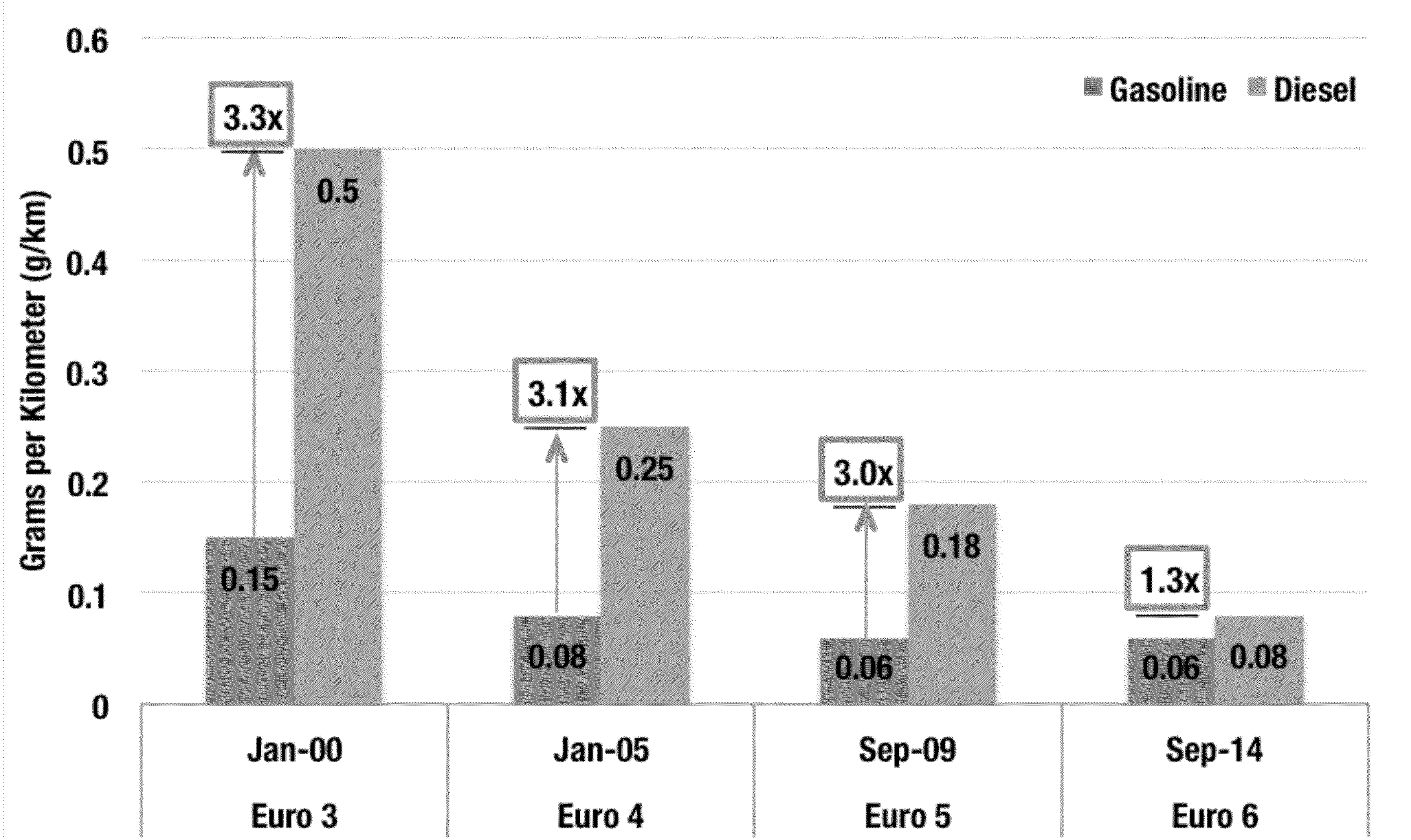
LDDV NOx Standards in Europe are not as stringent as LDGV



Emission Control Technologies: Gasoline

In-cylinder	Aftertreatment

• Air-Fuel ratio control
  • Fuel injection (TBI or MPI)
  • O_2 sensor (O2S, HO2S, UEGO)
• Geometry
  • Reduce crevices
  • Intake ports
  • Spark plug position
• EGR
	• Three-Way Catalyst (TWC)
	  • NOx, HC, CO
	
	• PM generally not an issue with port injected, but could become on GDI. Gasoline Particulate Filters (GPF)

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Emission Control Technologies: Diesel

In-cylinder	Aftertreatment
• Air-fuel management syst. • Rotary pump, Common-rail • Direct or Indirect Inj. • Low or High pressure • Turbocharging with intercooling • Variable geometry turbo (VGT) • Variable valve timing (VVT) • Geometry • Nozzle (sac vol., #holes, etc) • Comb. chamber • EGR system -NOx Control • Mechanic or Electronic • Cooled or not	• Diesel Oxidation Catalyst (DOC) • CO (90%), HC (70%) • SOF fraction of PM (10-50%) • Diesel Particulate Filter (DPF) • PM (95%) • PN • Lean NOx Trap (LNT) • NOx (70-90%) • Require ULSD • Selective Catalytic Reduction (SCR) • NOx (95%)

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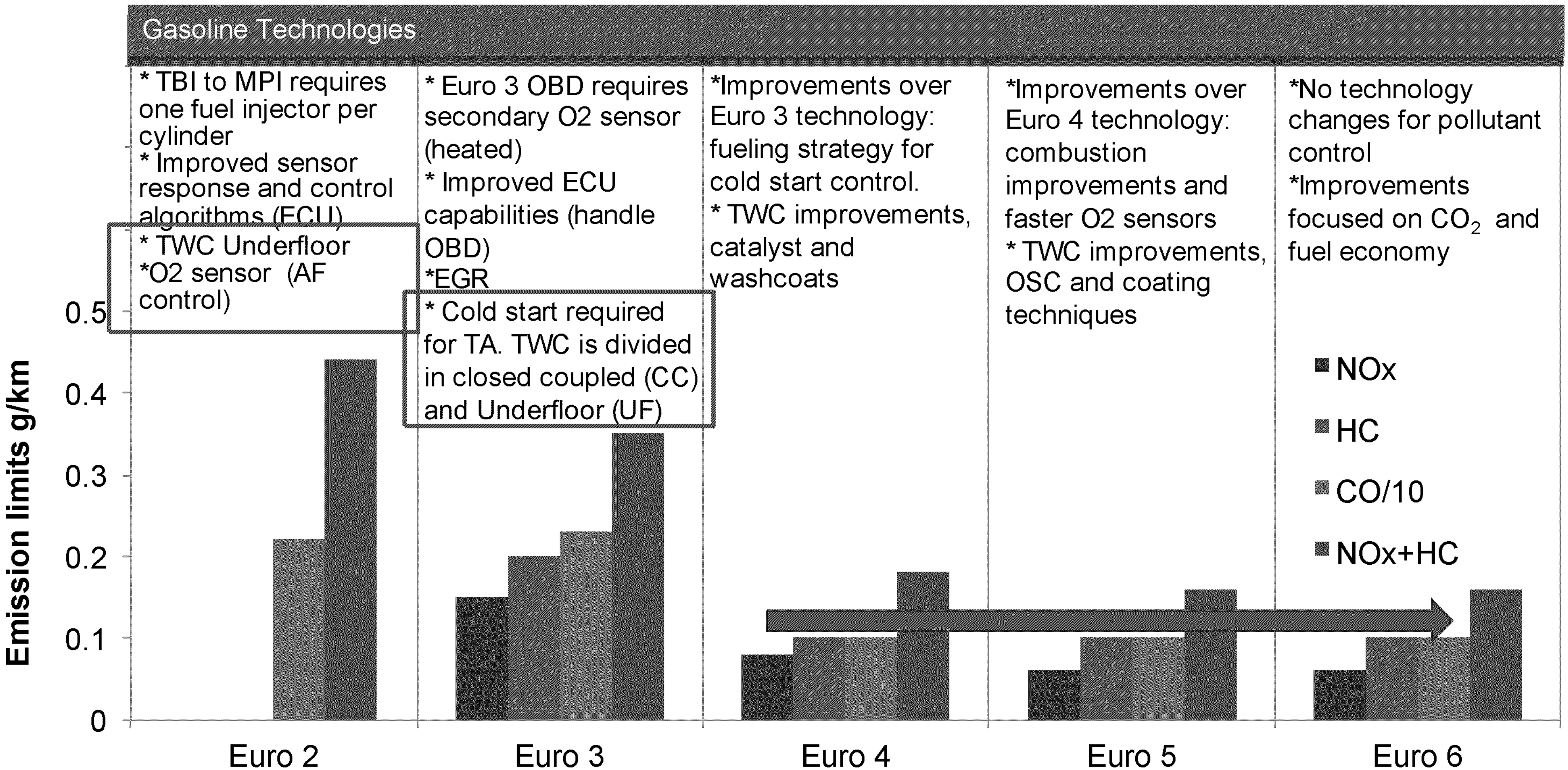
Technologies by Regulatory Level: Gasoline



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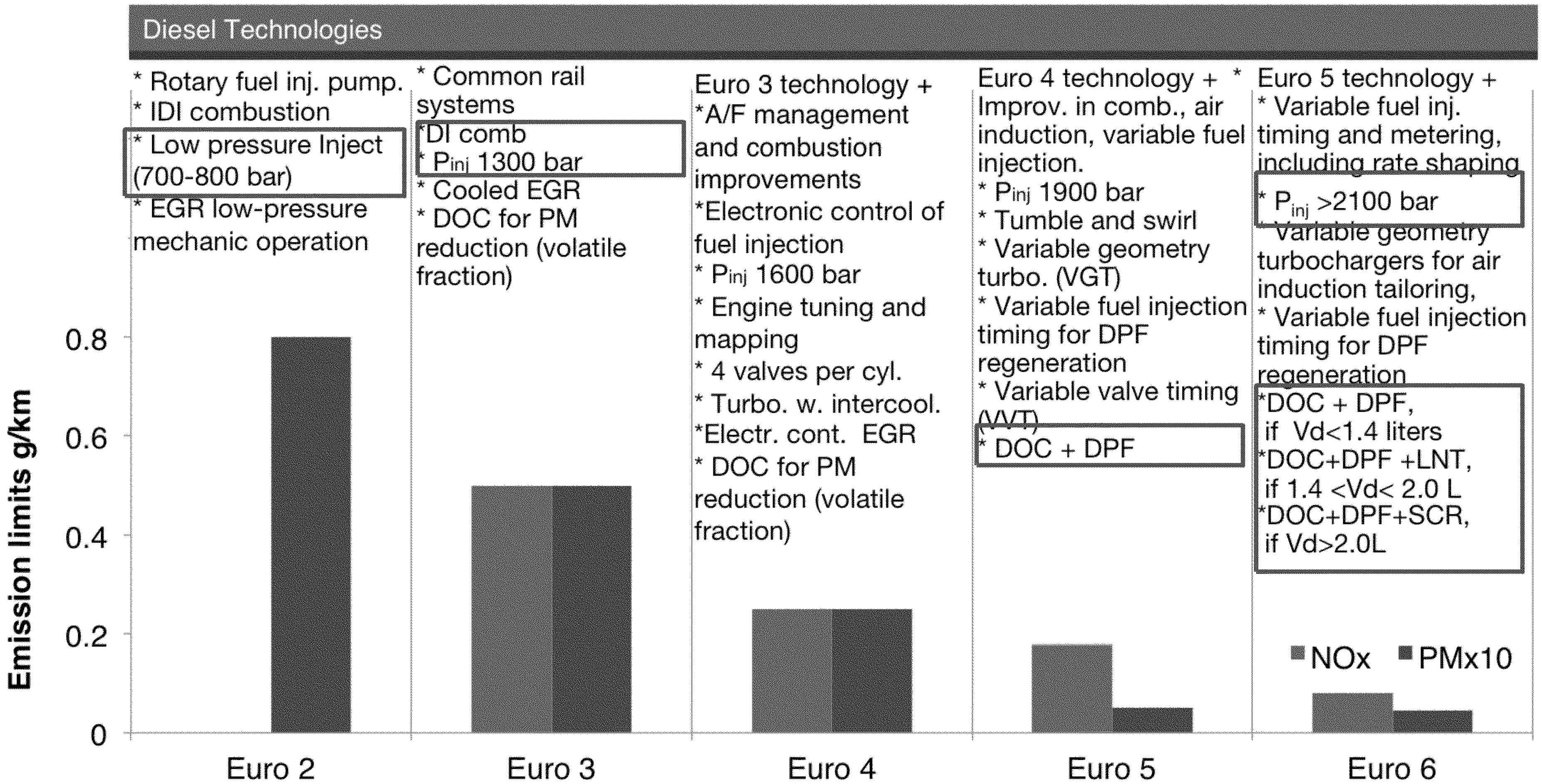
Technologies by Regulatory Level: Diesel



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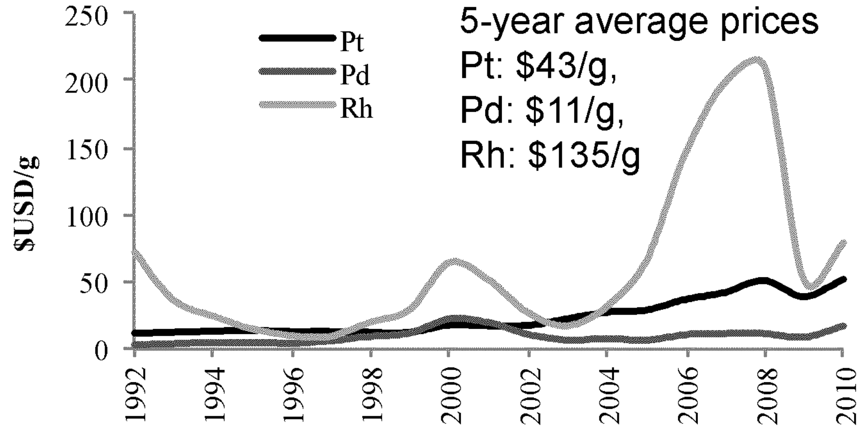
Gasoline LDV Technology Costs

Example: TWC Catalyst cost
Technology review supported technology improvements and reduced PGM loadings

Historic PGM Load

Region	Regulation	Pt, g/L	Pd, g/L	Rh, g/L
US	Tier 1	1.0-1.4	0.7-2.5	0.2
	NLEV	0.15-0.90	1.8-4.0	0.1-0.2
	Tier 2	0.1	1.3-2.6	0.1-0.2
EU	Euro 1	1.0	-	0.2
	Euro 2	1.0	-	0.2
	Euro 3	0.6-0.7	-	0.10-0.15
	Euro 4	-	0.6	0.10-0.15
	Euro 5	-	0.6	0.13-0.18
	Euro 6	-	0.6	0.13-0.18



Current PGM Load

Region	Regulation	Pt, g/L	Pd, g/L	Rh, g/L
US	Tier 1	0.1	1.0	0.1
	NLEV	0.1	1.3	0.1
	Tier 2	0.1	1.6	0.1
EU	Euro 1	0.1	0.5	0.1
	Euro 2	0.1	0.5	0.1
	Euro 3	0.1	0.6	0.1
	Euro 4	0.1	0.6	0.1
	Euro 5	0.1	0.7	0.1
	Euro 6	0.1	0.7	0.1

PGM loading Cost for each regulatory level for current technology, V_d= 2.0 L

Region	Regulation	SVR	CV, L	Cost, $USD
US	Tier 1	0.80	1.6	$47
	NLEV	0.90	1.8	$58
	Tier 2	1.00	2.0	$71
EU	Euro 1	0.80	1.6	$38
	Euro 2	0.85	1.7	$40
	Euro 3	0.90	1.8	$45
	Euro 4	0.95	1.9	$47
	Euro 5	1.00	2.0	$51
	Euro 6	1.00	2.0	$51

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Gasoline LDV Technology Costs

Estimated costs of emission control technologies for US and European gasoline LDVs, 2.0 L I4

Regulation	US			EU					
Cost item	**Tier 1**	**NLEV**	**Tier 2**	**Euro 1**	**Euro 2**	**Euro 3**	**Euro 4**	**Euro 5**	**Euro 6**
1. A/F control & engine-out emissions									
Oxygen sensor set (typical minimum required)	HO2S x2	HO2S x2	UEGO+ HO2S	O2S	O2S	HO2S x2	HO2S x2	UEGO+ HO2S	UEGO+ HO2S
Oxygen sensor set costs	$40	$40	$53	$16	$16	$40	$40	$53	$53
TBI/PFI Fuel system – 1/3 of cost (a)	$52	$65	$65	$52	$52	$65	$65	$65	$65
A/F management and combustion improvements	R&D	R&D	R&D	R&D	R&D	R&D	R&D	R&D	R&D
Faster microprocessor (b)	-	$4	$8	-	-	$4	$4	$8	$8
Engine modifications	$15	$20	$20	$15	$15	$15	$15	$20	$20
EGR system (c)	$25	$39	$39	$25	$25	$39	$39	$39	$39
Cost of hardware A/F control & engine-out emissions	**$132**	**$168**	**$185**	**$108**	**$108**	**$163**	**$163**	**$185**	**$185**
2. Aftertreatment systems									
TWC system (TWC catalyst + fitting elements)	$82	$105	$121	$73	$76	$92	$95	$101	$101
Exhaust pipe hardware	$12	$18	$18	$12	$12	$18	$18	$18	$18
Low thermal capacity manifold	-	$24	$24	-	-	$24	$24	$24	$24
Cost of aftertreatment systems	**$94**	**$147**	**$163**	**$85**	**$88**	**$134**	**$137**	**$143**	**$143**
3. Total cost of hardware [1+2]	**$226**	**$315**	**$348**	**$193**	**$196**	**$297**	**$300**	**$328**	**$328**
4. R&D, tooling, certification	**$24**	**$36**	**$42**	**$24**	**$24**	**$31**	**$42**	**$42**	**$42**
5. Total cost of emission control tech. [3+4]	**$250**	**$351**	**$390**	**$217**	**$220**	**$328**	**$342**	**$370**	**$370**

PAPER # 2013-01-0534

Diesel LDV Technology Costs

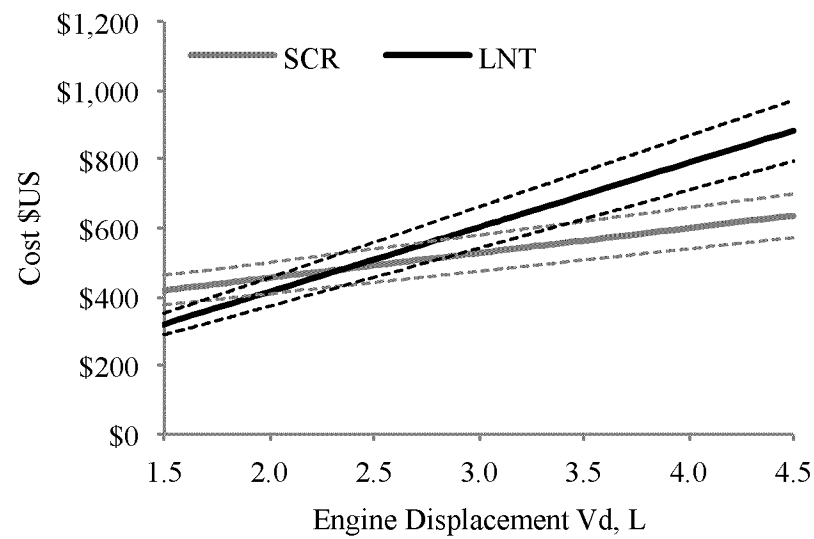
Example: Aftertreatment control system costs

SCR System, Vd= 2.0 L

No	Cost Item	
1	Average engine displacement, Vd, liters	2.0
2	Catalyst volume, CV (SVR=1.0), liters	2.0
3	Pt, Pd, and Rh are not required for NOx control	$0
4	NH3 catalyst, CV (SVR=0.2), 1 g/L PGM @ $43/g	$17
5	Total PGM ([3]+[4])	$17
6	Substrate and washcoat ($20/L*CV)	$40
7	Canning ($15*CV)	$30
8	**Total SCR catalysts**: PGMs + substrate+ washcoat	**$87**
9	Urea tank volume (8*Vd), liters	16
10	Urea tank cost	$114
11	Urea level sensor ($60 commercial price/2.5)	$24
12	Urea tank accessories (brackets, bolts, spacers)	$15
13	Urea pump ($130 commercial price/2.5)	$52
14	Urea injector ($86 commercial price/2.5)	$34
15	Tubing Stainless Steel ($35 commercial price/2.5)	$14
16	Urea Injection pipe section D2.5"x38cm	$14
17	Urea Injection mounting parts (brackets, bolts, gaskets, spacers, tubing connectors)	$15
18	Urea heating system- 200 W, 12 V DC.	$40
19	Temperature sensors (x2)	$42
20	Urea mixer	$50
21	**Total Urea System** ([9]+[10]+…+[20])	**$414**
22	Total Manufacturing: SCR Cat and urea syst.	$501
23	Labor costs with overhead	$48
24	Total Direct Costs to Manufacturing ([22]+[23])	$549
25	**Long term cost** (0.8*[24])	**$440**

Detailed part cost estimations was done for each aftertreatmemt system: DOC, DPF, LNT and SCR

System	Cost = f(V_d)
DOC	$\$DOC(V_d) = 37*V_d+6$
DPF	$\$DPF(V_d) = 135*V_d+53$
LNT	$\$LNT(V_d) = 188*V_d+27$
SCR	$\$SCR(V_d) = 72*V_d+297$



Diesel LDV Technology Costs

Estimated costs of emission control technologies for European diesel LDVs, 2.0 L I4

	Regulation	EU					
	Cost item	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
1.	A/F control & engine-out emissions						
	Fuel system - 50% of cost (a)	-	$50	$323	$355	$390	$429
	Turbocharger - 50% of cost (b)	-			$75	$75	$138
	Intercooler - 50% of costs (b)	-			$32	$32	$32
	VGT (extra cost) - 50% of costs (b)	-					$55
	EGR valves (c)	$30	$30	$30	$38	$38	$38
	EGR cooling system (c)		$36	$36	$44	$51	$58
	Engine mapping and tuning (d)	-	R&D	R&D	R&D	R&D	R&D
	Improvements on combustion chamber & nozzle geometry (e)	-	R&D	R&D	R&D	R&D	R&D
	Cost of A/F control & engine-out emissions	$30	$116	$389	$543	$586	$750
2.	Aftertreatment systems						
	Diesel oxidation catalyst (DOC) (f)	-	-	$78	$78	$78	$78
	Diesel particulate filter (DPF) (f)	-	-	-	-	$322	$322
	Lean NOx trap (LNT) (f)	-	-	-	-	-	$402
	Selective catalytic reduction (SCR) (g)	-	-	-	-	-	-
	Cost of aftertreatment systems (h)	$0	$0	$78	$78	$400	$802
3.	Total cost of hardware [1+2]	$30	$116	$467	$621	$986	$1,552
4.	Fixed costs (R&D, tooling, certification)	$26	$26	$51	$51	$51	$51
5.	Total cost of emissions control tech [3+4]	$56	$142	$518	$672	$1,037	$1,603

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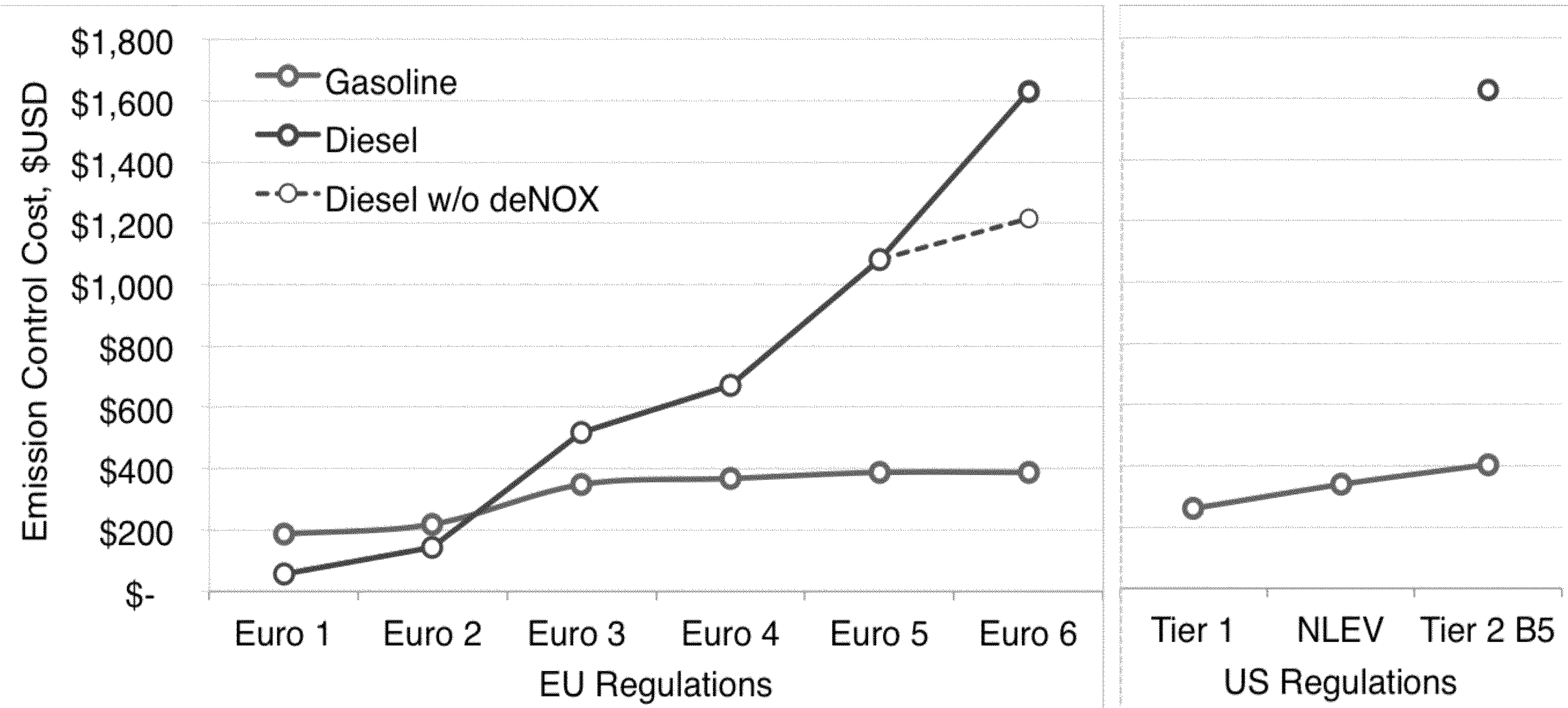
Estimated cost of LDV emission control technologies

Estimated direct manufacturing emission control technology cost for gasoline and diesel LDVs assuming a 2.0 L engine



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U.S. Tier 3 Emission Standards

US: Tier 3 Light Duty Emission Standards
(March 2014)

- Each Tier 3 bin has a NMOG+NO_X standard, as well as CO and HCHO standards
- 80% reduction in NMHC+NOX
- 70% reduction in PM
- New evaporative requirements
- 150k mile useful life (up from 120k)

Test cycle	Vehicle Class[1]	Tier 2	Model Year								
		2016[a]	2017[b]	2018	2019	2020	2021	2022	2023	2024	2025+
FTP	LDV/LDT1[b]	160	86	79	72	65	58	51	44	37	30
FTP	LDT2,3,4 and MDPV	160	101	92	83	74	65	56	47	38	30

Fleet-average NMOG+NO_X (FTP), by model year

US: Tier 3 Emissions Compliance
(March 2014)

- $72 per vehicle incremental cost after full phase-in:
  - Increased catalyst loadings (all vehicles)
  - Improved air/fuel control, particularly at cold start (all)
  - Optimized close-coupled catalyst (~60%)
  - Optimized thermal management (~40%)
  - Passive HC adsorbers (<5%)
  - Secondary air injection systems (~25% initially, then ramps down to <5%)
  - Improved evaporative emissions systems (all)

Tier 3 SFTP HC+NOx Standards versus Current Tier 2 Bin 2/3 Vehicles

2017 Standard = 103 mg/mi: more than 10 times current emission levels

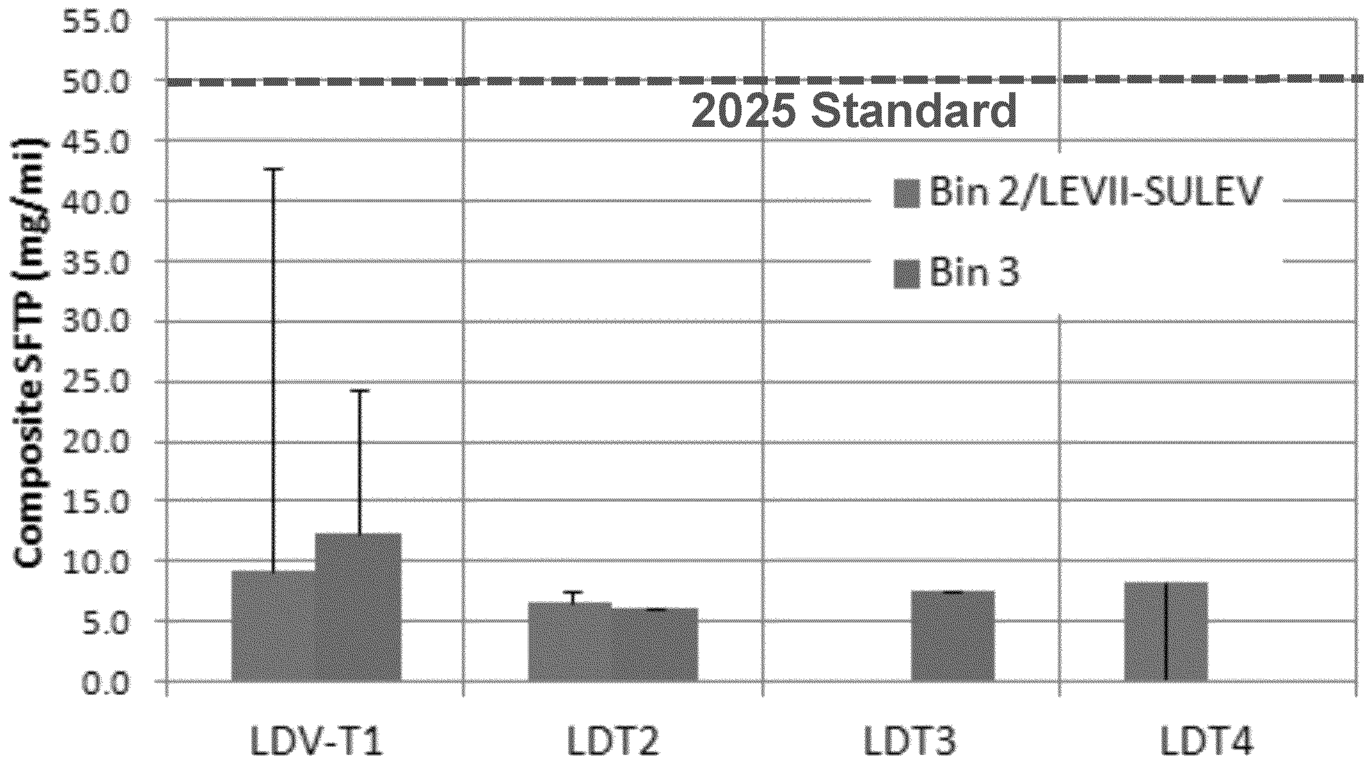


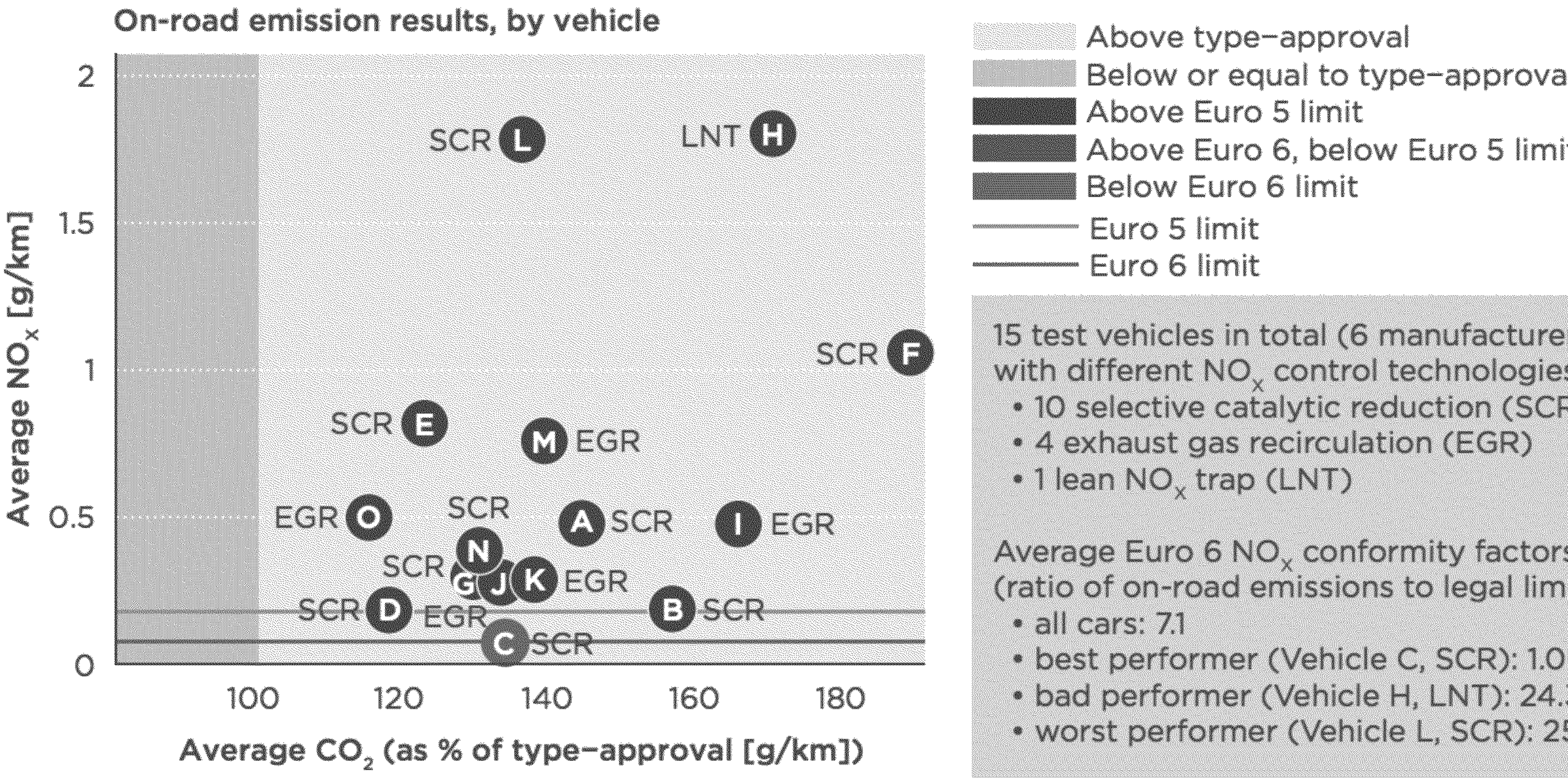
Figure 1-5: Mean and Maximum Composite SFTP Results for HC+NO_X for Test Groups certified to Bin-2 and Bin-3 Standards (bars and error-bars represent means and maxima for sets of test groups, respectively)

Graph from EPA RIA for Tier 3 proposed rule

In-Use Diesel NOx Emissions

On-road emissions of nitrogen oxides (NOX) from 15 Euro 6/Tier 2-B5 LDDVs measured by PEMS

Compiled EU and US data



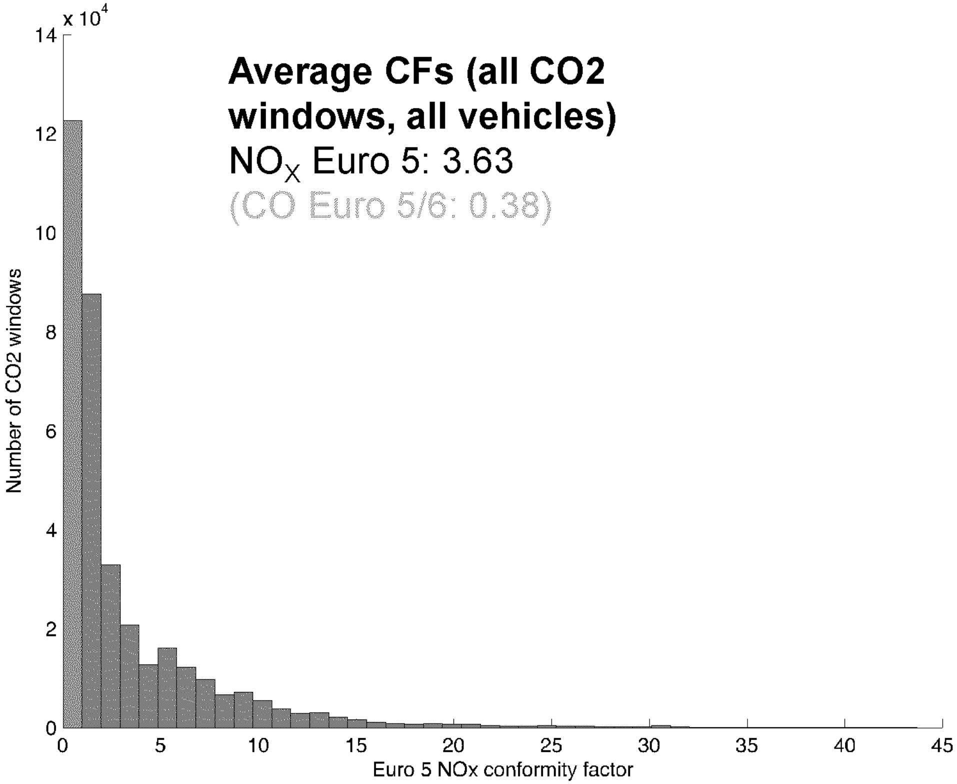
15 test vehicles in total (6 manufacturers), with different NO_x control technologies:
- 10 selective catalytic reduction (SCR)
- 4 exhaust gas recirculation (EGR)
- 1 lean NO_x trap (LNT)

Average Euro 6 NO_x conformity factors (ratio of on-road emissions to legal limits):
- all cars: 7.1
- best performer (Vehicle C, SCR): 1.0
- bad performer (Vehicle H, LNT): 24.3
- worst performer (Vehicle L, SCR): 25.4

Real-world exhaust emissions from modern diesel cars, October 11, 2014
http://www.theicct.org/real-world-exhaust-emissions-modern-diesel-cars

ICCT PEMS meta-analysis : NO_X conformity factors

(all vehicles and all trips)



Average CFs (all CO2 windows, all vehicles)

NO_X Euro 5: 3.63

(CO Euro 5/6: 0.38)

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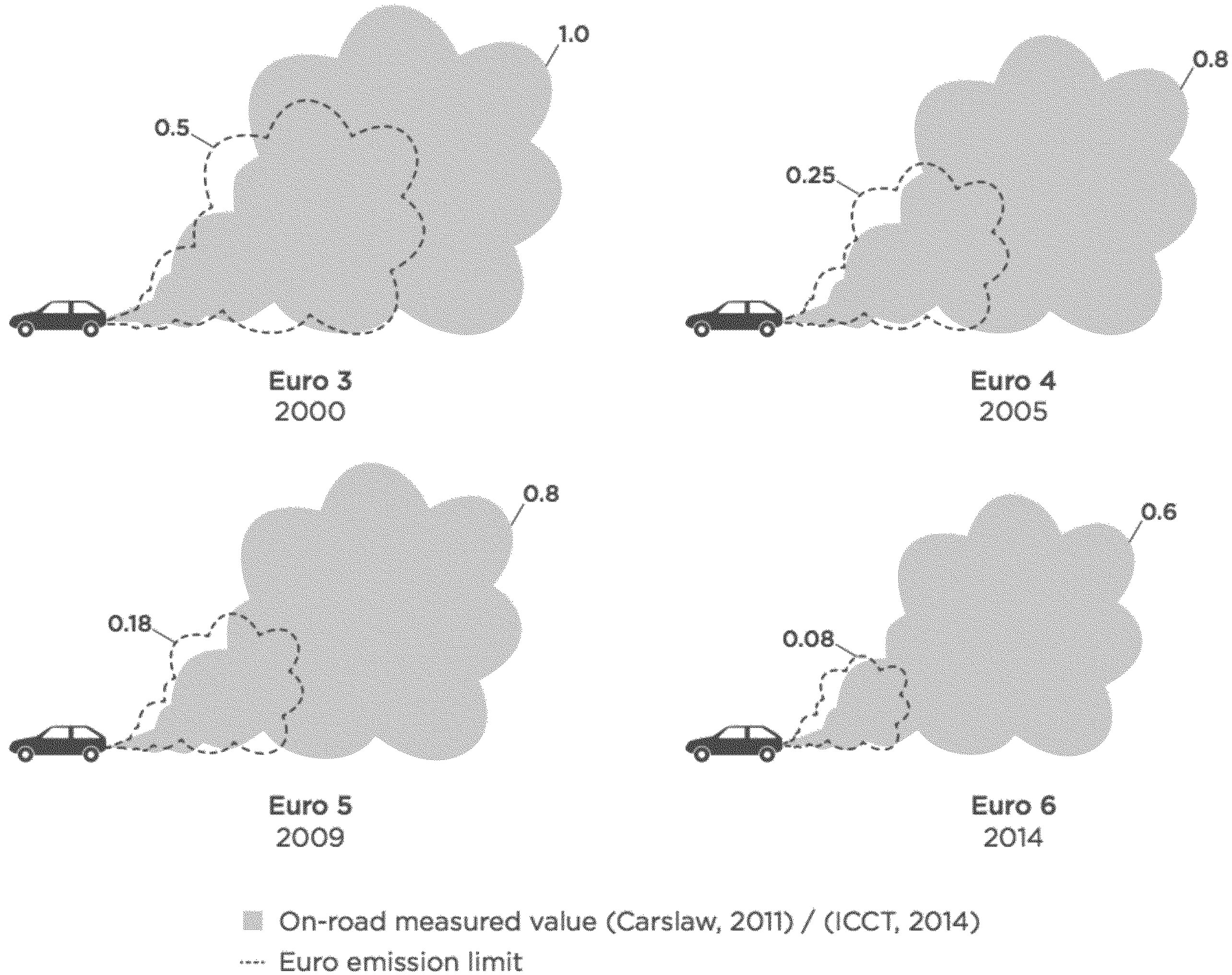
LDDV NOx emission limits reduced by 85% Euro 3 to Euro 6, but on-road emissions reduced only by 40%

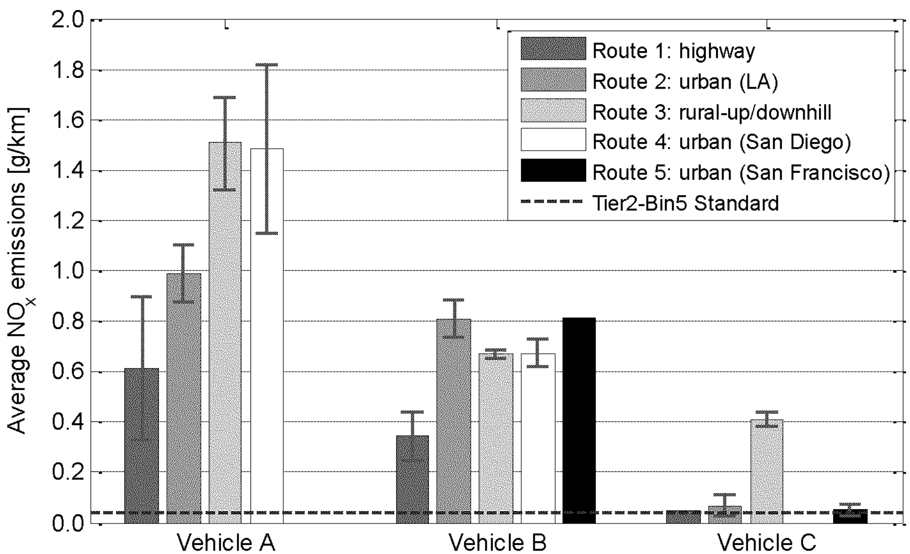


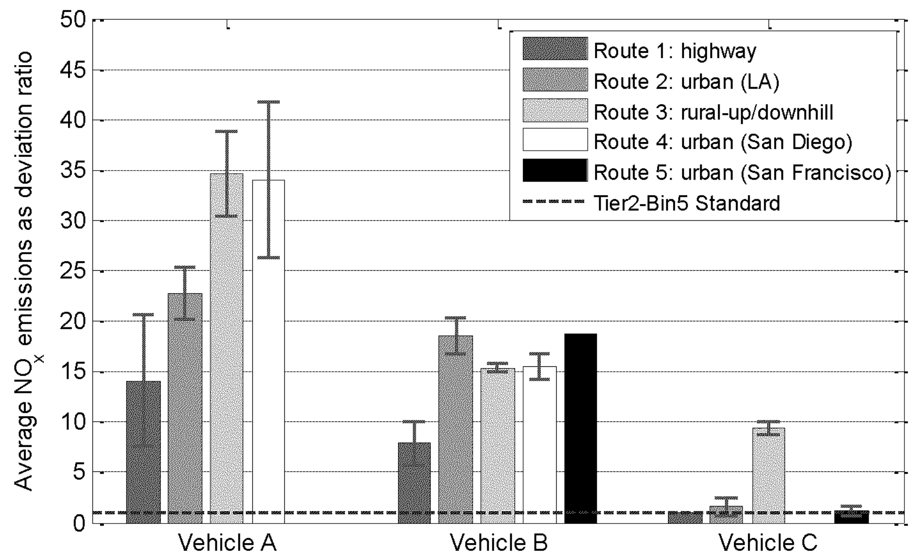
Source for Euro 3 to Euro 5: Carslaw et al. (2011). Recent evidence concerning higher NOX emissions from passenger cars and light duty vehicles. Journal of Atmosphereic Environment 45 (2011) 7053-7063.

Off-cycle, real world NOx emissions are not following the reduction trends set by standards

ICCT Data – US

- Vehicle A = Vehicle H in compiled data report
- Vehicle B = Vehicle F in compiled data report
- Vehicle C = Vehicle B in compiled data report





In-use NOx problem is likely calibration, not hardware, related:

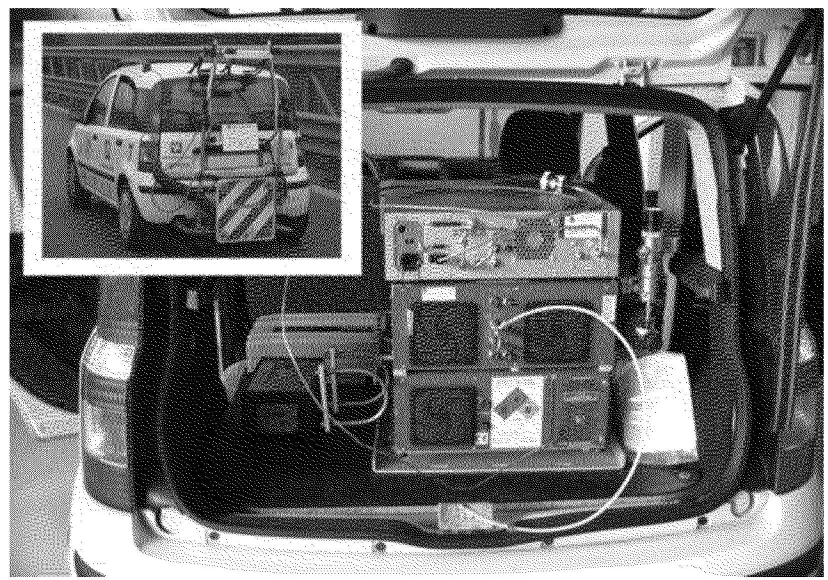
- Vehicle C maintained excellent in-use NOx except going uphill
- Vehicles A and B passed FTP and Euro6 standards on chassis dyno

http://www.theicct.org/use-emissions-testing-light-duty-diesel-vehicles-us

Europe's RDE-LDV process

What is it?

- An amendment to Euro 6 standards to make on-board (PEMS) testing **part of type-approval**
- Stakeholder working group is trying to define boundary conditions and how the data should be analyzed and reported
- Pilot phase to start in 2015, implementation in 2017
- Likely driver of changes in Diesel NO_X aftertreatment; implications on small Diesel PC market



Implications

- FTP/NEDC are inadequate for diesel NOx control
  - Need higher loads and more transient operation
  - Europe adoption of WLTP starting in 2017 will help:
    - But is the WLTC adequate?
    - What about the rest of the world following Euro standards?
- In-use testing and/or defeat device requirements are essential
  - US routinely conducts in-use testing and has defeat device requirements
  - Europe in the process of adopting PEMS requirements via Real Driving Emissions (RDE) process
- US06 NOx standards are not stringent enough

Closing Thoughts

Main messages

- Very clean vehicle technologies are already cost-effective and costs will continue to decline
- Standards are effective at bringing health and climate benefits
- Despite progress in developed countries, current penetration of best-practice standards in developing countries is insufficient to limit the worsening in health impacts
- Good standard design should ensure that the gap between real-world and certified emissions stays small

Policy trends

- Over the next five years, major vehicle markets are likely to have adopted low sulfur diesel fuel (< 50 ppm), Euro VI or better vehicle emission standards, and robust fuel economy standards
- Greater focus on real world driving emissions – both conventional pollutants and CO2 emissions
- Confluence of climate science and increasing levels of urban air pollution will draw regulatory attention to diesel particles
- Fuel quality will play a major role in determining the effectiveness of diesel aftertreatment technologies – second tier markets may opt for 50 ppm rather than 10 ppm
- Future international agreements are likely to include elements of transportation policies that will influence national and local level policies

Thank you for your attention!

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ON CLEAN TRANSPORTATION